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THE HORSESHOE FAULT

Evidence for Prehistoric Surface-Rupturing Earthquakes in Central Arizona

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Have earthquakes strong enough to rupture the ground surface occurred on faults in central Arizona during the recent geologic past? Could such earthquakes happen in the future? If so, where are they most likely to occur?

The Seismotectonics and Geophysics Section of the U.S. Bureau of Reclamation has, during the last 6 years, been working on answering these questions (Anderson and others, 1986, 1987; Anderson, 1990; Piety and Anderson, 1990). The Bureau of Reclamation is interested in earthquakes because it is responsible for the safety of eight major dams in central Arizona, including Horseshoe Dam on the Verde River (Figure 1). All but one of these dams were built between 1908 and 1946, long before anyone realized that strong earthquakes could occur in this region. The possibility of such earthquakes was not readily recognized, partly because earthquakes large enough to rupture the ground surface have not been observed historically within Arizona (DuBois and others, 1982; Stover and others, 1986).

Recognition of the potential for strong earthquakes in Arizona arose in the middle 1970's, when geologists began to search the State for evidence of prehistoric surface-rupturing events (Soule, 1978; Morrison and others, 1981; Menges and Pearthree, 1983; Pearthree and others, 1983; Pearthree and Scarborough, 1984). Interestingly, these studies revealed that such evidence is common in Arizona. The evidence chiefly consists of scarps, or abrupt breaks, on gently and evenly sloping surfaces of alluvial deposits. Because these scarps are associated with known faults and are similar in appearance, size, and length to scarps formed during historical earthquakes throughout the world, geologists infer that the scarps in Arizona formed during earthquakes that were strong enough to rupture the ground surface. Such earthquakes in the western United States are typically larger than about magnitude 6, which is large enough to cause significant damage to nearby, inadequately designed or poorly constructed structures. Because scarps

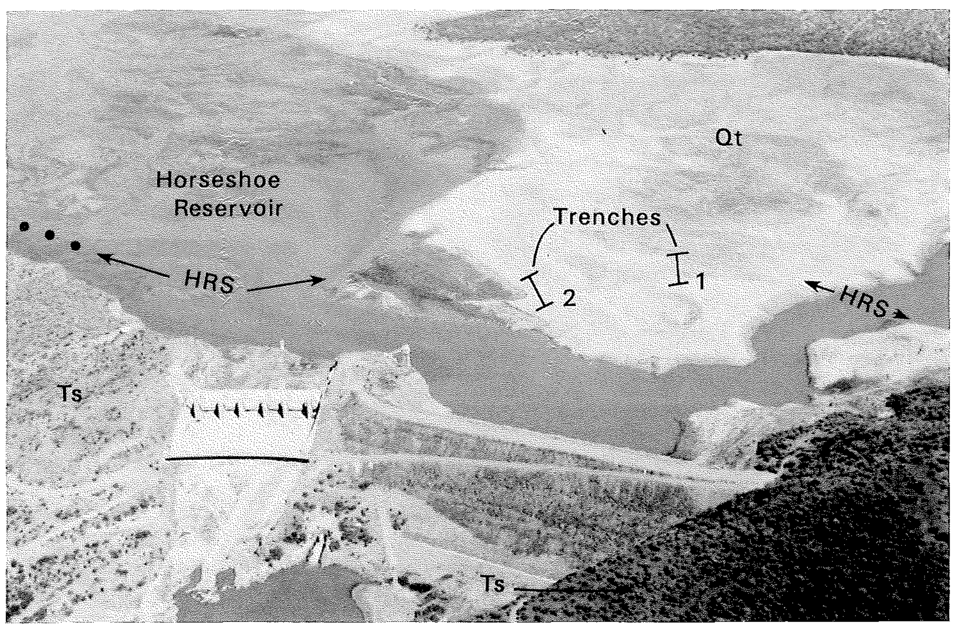

Figure 1. Aerial view of Horseshoe Dam (foreground). This view toward the north-northwest shows the curving north-facing scarp on the terrace surface (Qt) along the Horseshoe Reservoir segment (HRS) of the Horseshoe fault, a segment that was only recently identified. The approximate locations of two trenches excavated across this scarp are shown. (See section titled "Horseshoe Reservoir Segment.") Ts indicates tuffaceous sedimentary and volcanic rocks of late Tertiary age (Figure 3).

are eventually eroded from the landscape, those that formed during the last several hundred thousand years are easiest to recognize. Furthermore, scarps that indicate multiple ground-rupturing earthquakes along a fault during the last few hundred thousand years may be the most likely sites of future ground-rupturing earthquakes and, thus, are of greatest interest to those who assess the potential hazard to manmade structures.

Most faults in Arizona that display evidence of activity during the last 2 million years (m.y.; the Quaternary Period) lie within a diffuse band that trends diagonally across the State from the northwest to the southeast (Pearthree and others, 1983) and extends beyond its borders (e.g., the numerous faults in southwestern Utah and southern Nevada [Wallace, 1981] and the Pitaycachi fault in northern Sonora, Mexico [Pearthree, 1986; Pearthree and others, 1990]). This band of faults roughly coincides with a northwest-trending, poorly defined concentration of historical seismicity (Sumner, 1976; Pearthree and others, 1983) and the Transition Zone physiographic province (Peirce, 1984, 1985; Figure 2). The Horseshoe fault, which we investigated as part of a seismotectonic study of Horseshoe and Bartlett

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Dams, lies within both the Transition Zone and the northwest-trending band of Quaternary faults (Figure 2).

HORSESHOE FAULT

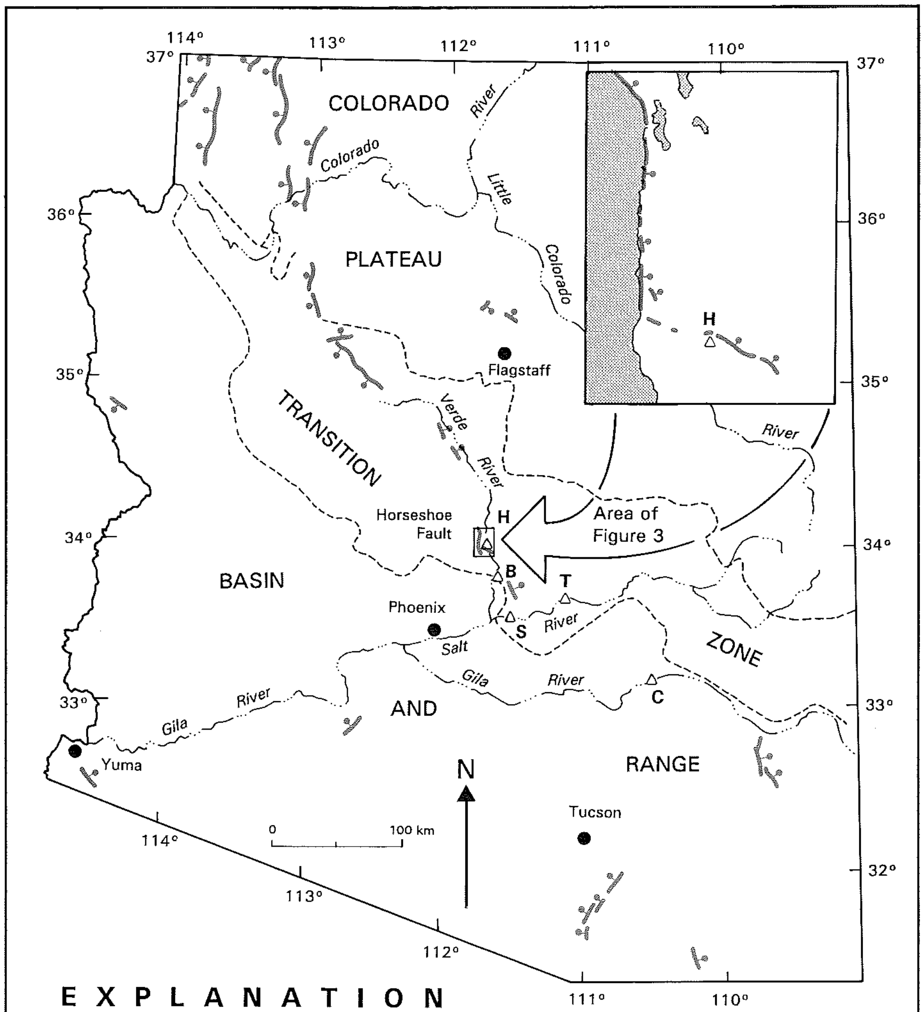
The Horseshoe fault is a north-trending normal fault that has characteristics similar to those of other faults within the Transition Zone that show evidence of Quaternary activity. Although our study focused on the Quaternary displacement along the Horseshoe fault, evidence for older displacement is also preserved. The basin east of and adjacent to the Horseshoe fault, which we informally call the Horseshoe basin, is filled with Tertiary sediments and volcanic rocks that consist of at least two distinct units: an older one containing abundant volcanic rocks (basalt, volcanic breccia, and tuffaceous sediment) and a younger, finer grained unit containing markedly fewer volcanic rocks (predominantly mudstone with some conglomerate and sandstone). The older unit dips steeply and contains numerous faults. An isotopic age on a basalt suggests that the older unit was deposited about 15 m.y. ago (Scarborough and Wilt, 1979). In contrast, the younger unit displays only minor deformation and may have been deposited between 10 m.y. and 5 m.y. ago (Scarborough and Wilt, 1979).

The lithologic characteristics and ages of these two units suggest that the timing of the main phase of activity along the Horseshoe fault may be similar to that along other basin-bounding faults in Arizona. This activity began between about 15 m.y. and 10 m.y. ago and may have diminished or ceased between about 8 m.y. and 6 m.y. ago (Scarborough and Peirce, 1978; Shafiqullah and others, 1980; Menges and McFadden, 1981; Menges and Pearthree, 1989). This period of late Tertiary activity, called the Basin and Range disturbance, affected many of the normal faults in the Transition Zone and adjacent Basin and Range Province in Arizona. This disturbance is thought to be primarily responsible for the alternating ranges and basins that now characterize large portions of these two physiographic provinces.

The Horseshoe fault is one of several faults in the central Transition Zone that were active during the late Tertiary and that either have been reactivated during the Quaternary or have continued to be active at lower rates (Pearthree and others, 1983). Compared to other possibly reactivated faults in the area (e.g., the Big Chino, Verde, and Sugarloaf faults; Figure 2), the Horseshoe fault is unusual because it is composed of two nearly perpendicular strands, only one of which is along a range front (Figures 2 and 3). One strand, which we informally call the Hell Canyon segment, trends almost due north, separating an unnamed mountain range to the west from Horseshoe basin. The other strand, which we informally call the Horseshoe Reservoir segment, trends west-northwest, slicing obliquely across Horseshoe basin. Both strands of the Horseshoe fault exhibit evidence for surface ruptures during about the last 300,000 years.

Hell Canyon Segment

The Hell Canyon segment separates Precambrian granitic rocks that form the unnamed mountain range west of the fault from the Tertiary sedimentary and volcanic rocks that fill Horseshoe basin (Figures 3 and 4). This fault segment, which is 11 to 12 kilometers long and dips eastward beneath the basin, was recognized by earlier workers (Ertec, 1981; Morrison and others, 1981; Menges and Pearthree, 1983; Pearthree and



EXPLANATION

Probable late Quaternary faults (displacement occurred during the last 150,000 years); bar and ball on downthrown side.

Approximate boundaries of the three physiographic provinces of Arizona.

Drainages.

Granitic rocks (Early Proterozoic; 1,650 m.y. to 1,750 m.y. old).

Δ Dams for which U.S. Bureau of Reclamation seismotectonic reports have been completed:
B-Bartlett Dam (Piety and Anderson, 1990).
C-Coolidge Dam (Anderson, 1990).
H-Horseshoe Dam (Piety and Anderson, 1990).
S-Stewart Mountain Dam (Anderson and others, 1986).
T-Theodore Roosevelt Dam (Anderson and others, 1987).

***Figure 2.** Probable late Quaternary (active during the last 150,000 years) faults and their relationship to the three major physiographic provinces in Arizona. The faults have been modified from Menges and Pearthree (1983) and Scarborough and others (1986); the boundaries of the physiographic provinces are from Peirce (1984).*

Scarborough, 1984). Its location is easily identified by lineaments created by differences in vegetation and by the abrupt contact between the Precambrian and Tertiary rocks (Figure 5). These features, however, are not necessarily indicative of Quaternary surface rupture along the fault.

Quaternary surface rupture is manifested by scarps on the relatively smooth surfaces of alluvial fans estimated to be of Pleistocene age (between 2 m.y. and 10,000 years old). These alluvial fans are composed of boulders, cobbles, and sand eroded from the adjacent range. Their surfaces slope 1° to 13° toward the Verde River away from the range front, except where the scarps abruptly steepen the slopes to 10° to 27°. The scarps, which are preserved discontinuously along some 9 kilometers of the Hell Canyon segment, displace the alluvial-fan surfaces from 2 to 5 meters (Figures 3 and 6). The scarps' alignment with the faulted contact between the Precambrian and Tertiary rocks and their roughly perpendicular orientation to drainages that issue from the range strongly indicate that the scarps were formed by surface-rupturing earthquakes along the fault rather than by erosion along the drainages that flow into the Verde River.

The scarps demonstrate that the Hell Canyon segment has experienced at least one, and possibly as many as three, strong earthquakes since the alluvial fans were deposited. Unfortunately, the ages of these alluvial fans could not be determined with any precision. Characteristics of the scarps themselves, however, suggest that at least one, and probably two, surface ruptures occurred during the late Quaternary (within about the last 150,000 years). The scarps are straight, relatively steep (maximum slope angles between 10° and 27°, with scarp heights of 2 to 7.5 meters), and not markedly dissected or modified by stream erosion. In other areas of the western United States, where scarps have been dated through the use of radiocarbon techniques or by the identification of volcanic ash layers, scarps with the above characteristics are thought to have formed during the last 30,000 to 15,000 years (Wallace, 1977; Bucknam and Anderson, 1979). Because scarp characteristics are influenced by many factors besides age, direct comparison of these characteristics among areas with different climates, rock types, or erosion rates is questionable. The straightness, steepness, and location of the scarps near the base of the range front, however, suggest that only limited erosion has occurred along this fault segment since the most recent surface-rupturing earthquake. From these characteristics, we infer that at least one, and probably two, surface ruptures took place on the Hell Canyon segment during the late Quaternary; the most recent rupture may have occurred during the last 30,000 to 15,000 years.

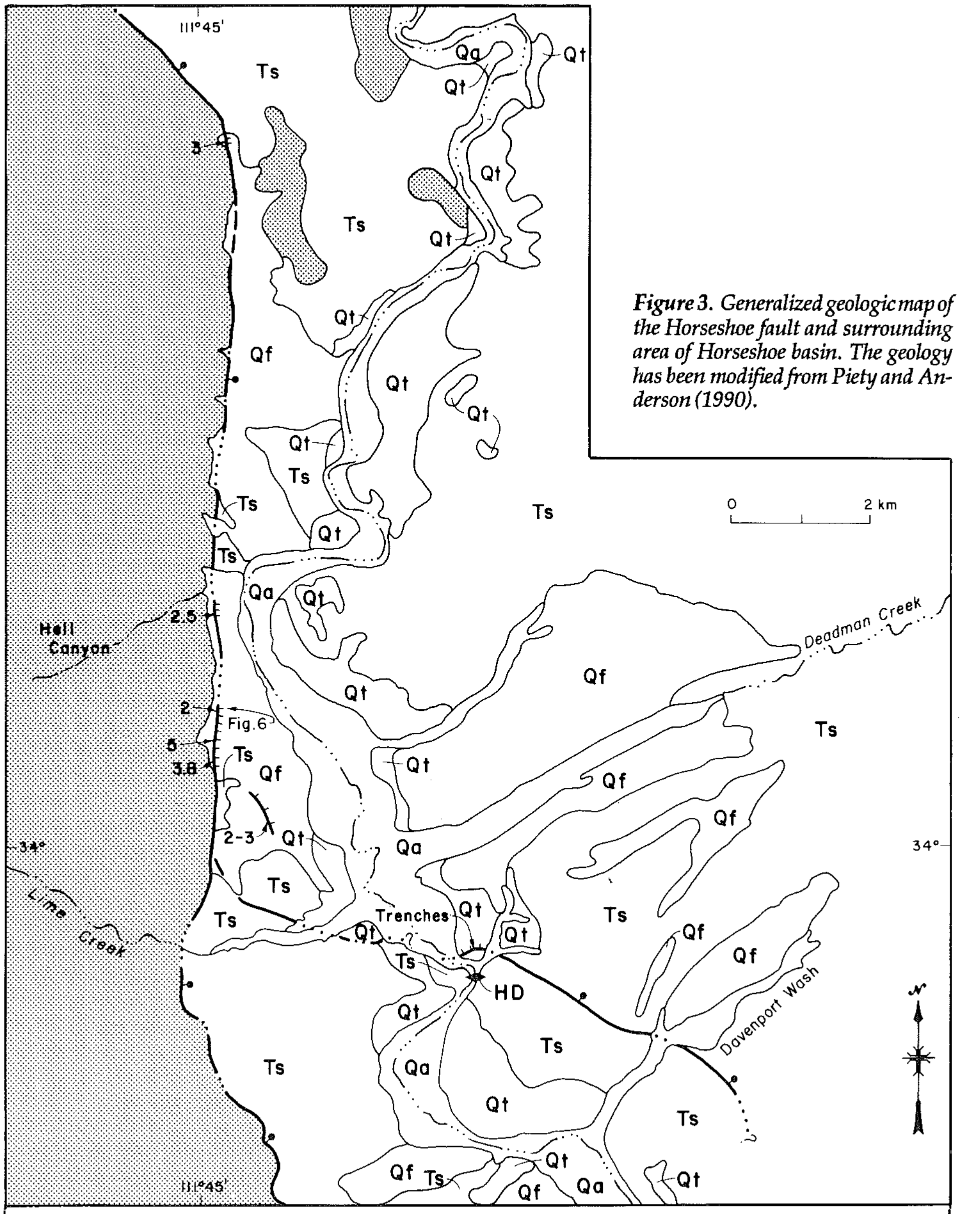


Figure 3. Generalized geologic map of the Horseshoe fault and surrounding area of Horseshoe basin. The geology has been modified from Piety and Anderson (1990).

Qa -- Floodplain deposits (Holocene)

Qf -- Alluvial-fan deposits (Pleistocene)

Qt -- Terrace deposits along the Verde River (Pleistocene and Pliocene?)

Ts -- Tuffaceous sediment, volcanic rock (chiefly basalt), volcanic breccia, conglomerate, sandstone, and mudstone (Pliocene? and Miocene)

Granitic rocks (Early Proterozoic, 1,650 m.y. to 1,750 m.y. old)

Horseshoe fault -- Solid where well located or approximately located, dotted where concealed; bar and ball on downthrown side. Hachures indicate scarps on Pleistocene alluvial fans. Numbers indicate vertical surface displacement (in meters) estimated from topographic profiles.

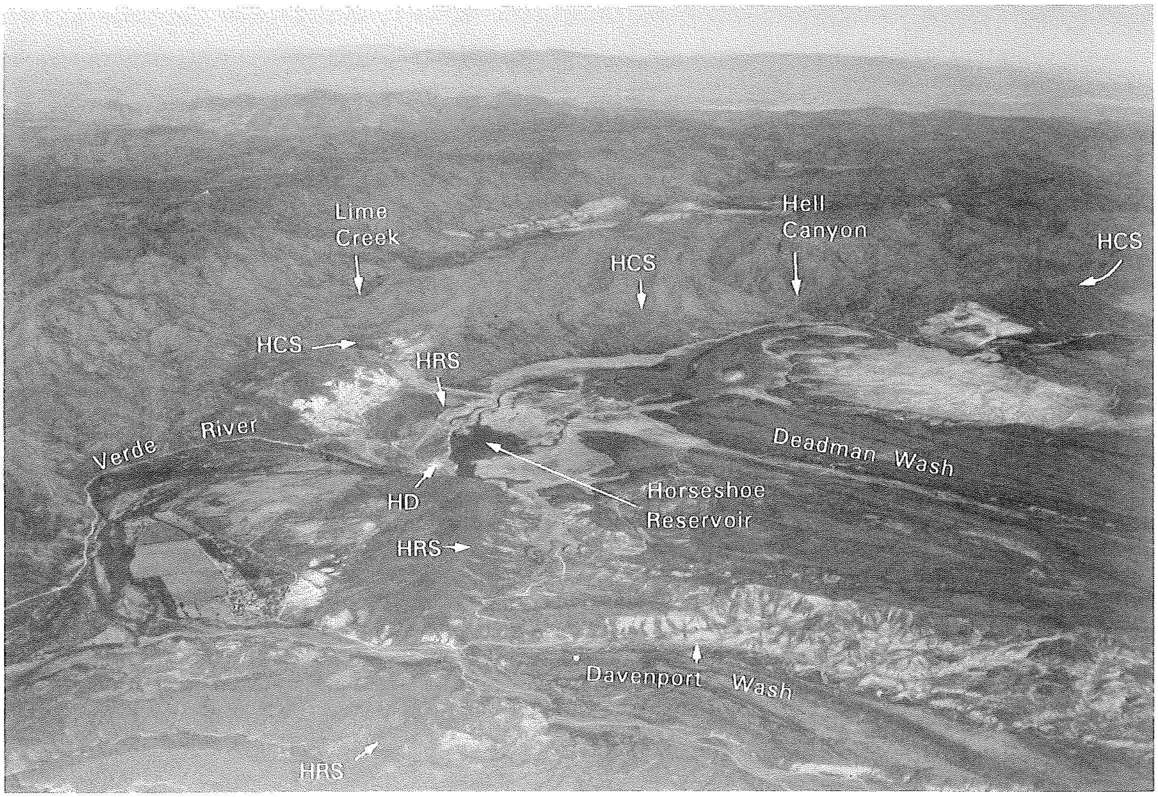
Drainages

HD -- Horseshoe Dam (Horseshoe Reservoir not shown)

Horseshoe Reservoir Segment

The Horseshoe Reservoir segment, which trends west-northwest across Horseshoe basin, separates south-southwest-dipping Tertiary basalt, basaltic breccia, and tuffaceous sandstone on the south from nearly horizontal Tertiary mudstone on the north. This segment, which is 9 to 10 kilometers long and dips northward (Figure 3), was not identified by previous workers, probably because much of this segment is usually concealed by Horseshoe Reservoir. The fault is marked by a lineament along the strike of a basaltic bed that is more resistant to erosion than the weakly cemented mudstone adjacent to it, and by a steeply dipping fault contact between volcanic breccia and

Figure 4. Aerial view toward the northwest of the two segments of the Horseshoe fault. The Hell Canyon segment (HCS) trends along the range in the middle ground. The Horseshoe Reservoir segment (HRS) trends away from the viewer toward the Hell Canyon segment. Horseshoe Dam (HD) is partially concealed in the middle ground.



mudstone exposed in Davenport Wash (Figure 3).

In contrast to the discontinuous scarps preserved along some 9 kilometers of the Hell Canyon segment, evidence for Quaternary surface rupture on the Horseshoe Reservoir segment is readily apparent at only one locality: on a terrace of the Verde River just north of Horseshoe Dam (Figure 3). A curving, north-facing scarp is preserved on this terrace surface, but is visible only when water levels in Horseshoe Reservoir are low (Figure 1). The displacement history of this segment was determined by excavating two trenches across this scarp (Figures 1 and 3). Detailed mapping of the fault and descriptions of the deposits exposed in the trenches clearly show that surface-rupturing earthquakes accompanied by about 1 meter of displacement occurred at least twice on the Horseshoe Reservoir segment since deposition of the Verde River terrace gravel. Evidence for surface rupture is indicated by a step in the surface of the fluvial gravel and by alignment of gravel clasts, which were rotated to a near-vertical orientation as the gravel deposits on adjacent sides of the fault slid past each other (Figure 7). After this step or scarp formed on the terrace surface, exposed gravel clasts fell from the scarp and accumulated at its base. Sand deposited by water flowing along the base of the scarp or by wind blowing down the Verde River Valley filled in and eventually covered the scarp. The gravel that accumulated at the base of the scarp and some of the sand that was deposited against the scarp have also been disrupted by fault displacement, indicating at least one additional surface rupture.

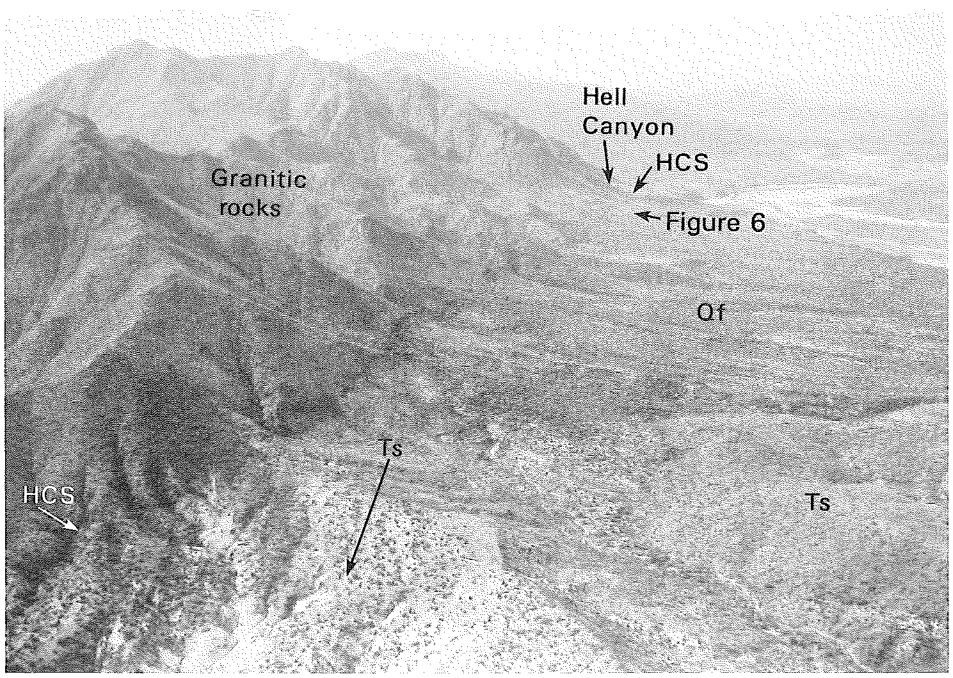


Figure 5. Aerial view toward the north-northwest along the Hell Canyon segment (HCS) of the Horseshoe fault. Lime Creek is just out of view in the foreground, and Hell Canyon is in the background. Tuffaceous sedimentary and volcanic rocks of late Tertiary age (Ts) and alluvial-fan deposits of Quaternary age (Qf) are juxtaposed against granitic rocks in the range (Figure 3).

Soils developed on the deposits exposed in the trench were used to estimate the time between surface ruptures and the time since the last rupture (for a description of methods, see Birkeland, 1984). Because of the height (18 meters) of the terrace surface above the present floodplain of the Verde River and the strong soil development on the fluvial gravel, we infer that the gravel was deposited at most about 300,000 years ago. Thus, the two or more surface ruptures exposed in the trench must be younger than this. The moderate to strong soil development during the interval between two of the surface ruptures indicates that about 50,000 to 100,000 years separated the two events. Furthermore, the relatively weak soil developed on the sand that overlies all deposits displaced by the fault suggests that the youngest rupture occurred before 10,000 to 20,000 years ago. Our best estimate for the timing of these surface ruptures on the Horseshoe Reservoir segment is about 15,000 years ago for the most recent event and about 100,000 years ago for the penultimate event. Based on empirical relationships between rupture length, apparent surface displacement, and earthquake magnitude developed by Bonilla and others (1984), we estimate that these earthquakes were about magnitude 6.5 to 7.

FUTURE SURFACE-RUPTURING EARTHQUAKES

Earthquakes strong enough to cause rupture of the ground surface have undoubtedly occurred on the Horseshoe fault during the last few hundred thousand years. Could such earthquakes happen in the future? Assuming that displacements took place simultaneously on both segments of the Horseshoe fault and that these displacements during the last few hundred thousand years have been approximately evenly spaced, we estimate that an interval of 50,000 to 100,000 years separates the surface-rupturing earthquakes. Because the youngest rupture occurred before 10,000 to 20,000 years ago, it is possible that several tens of thousands of years may pass before the next surface-rupturing earthquake on the Horseshoe fault. On the other hand, it is equally possible that surface ruptures are not evenly spaced. After several hundred thousand years of quiescence, the current phase of activity may be just beginning. Evidence from well-studied faults in other areas indicates that surface-rupturing earthquakes on some faults recur within a relatively short period that is followed by a relatively long period without such earthquakes (Schwartz, 1988). Such temporal clustering of surface-rupturing earthquakes along the Horseshoe fault cannot be ruled out. Because accurate earthquake prediction is not yet possible and because additional data that future studies might provide are needed to improve our understanding of fault behavior in Arizona, faults with evidence of Quaternary activity in central Arizona, including the Horseshoe fault, should be considered potential sites for future surface-rupturing earthquakes.

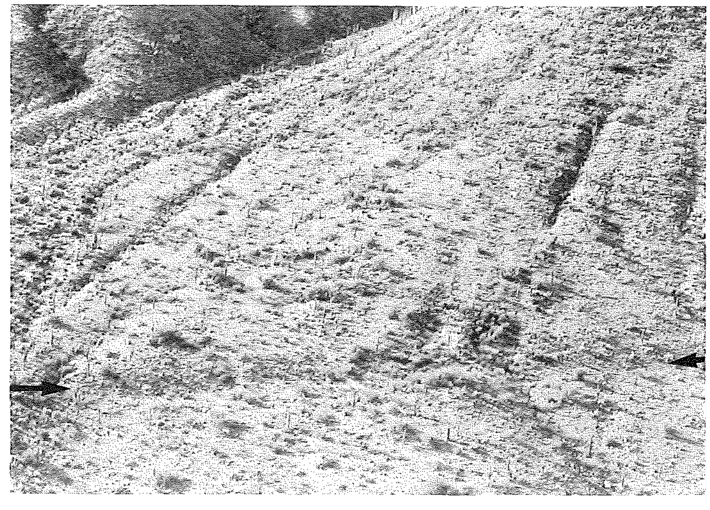


Figure 6. *Aerial view toward the west of a linear east-facing scarp (between arrows) along the Hell Canyon segment of the Horseshoe fault between Lime Creek and Hell Canyon (Figures 3 and 5). The displacement of the alluvial-fan surface across this scarp is about 2 meters. The slope of the alluvial-fan surface is 10° to 13°; the maximum slope of the scarp is about 27°.*

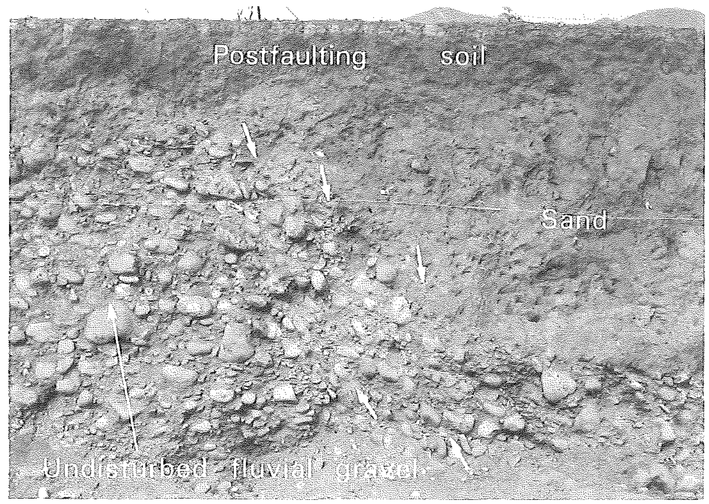


Figure 7. *The Horseshoe Reservoir segment (HRS) of the Horseshoe fault exposed in Trench 1 excavated into the terrace just north of Horseshoe Dam (Figure 1). The west wall of the trench is shown. The fault displaces fluvial gravel that was deposited by the Verde River and is now preserved as a terrace about 18 meters above the river. The fault is marked both by the step in the gravel surface and by the gravel clasts that have been rotated and aligned (sheared) by at least two ruptures. The arrows indicate zones along which the gravel clasts have been rotated by displacement on the fault. Sand deposited by water flowing along the base of the scarp or by wind blowing down the Verde River Valley has partially covered the scarp. A weak soil has developed in this sand (postfaulting soil) since the last displacement on the HRS.*

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